LARGE AREA BLACK BODY SOURCE FOR ITER ECE IN SITU CALIBRATION

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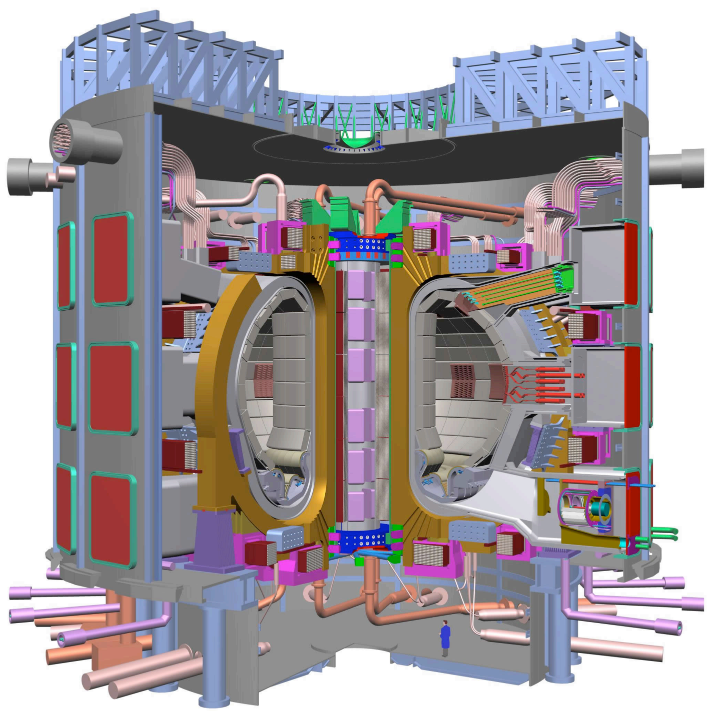
Abstract

- Development and testing of a hot calibration source for the ECE systems on ITER is underway. The source is intended to meet the requirements described in DDD55 Overview of Diagnostics. The requirement is for two 200 mm diameter sources. One will operate at atmospheric pressure and be well removed from the experiment. The other will operate in vacuum near the plasma. Both will operate at temperatures up to 800 °C. Here we report on the development of a prototype hot calibration source and of a realistic thermal model of the hot calibration source that will be used in simulations of the thermal properties of the source. Selection of a reliable heating method is challenging. Heating methods under consideration will be discussed.

- *Supported by US-IPO under PPPL-S0007684-R*



ITER Calibration Source Specification

- The ITER design documents specify the requirements of the ITER ECE calibration system.
  - All parts of the source (active face, heating/cooling elements, temperature measuring instrumentation, support structure) must be fully compatible with the high vacuum and high radiation flux environment inside a diagnostic port plug in the ITER machine. The source is not in a direct line of sight of the plasma, but is behind ~1m of shielding. Results of calculations of the radiation flux and nuclear heating at the location of the source are available from the ITER JCT.
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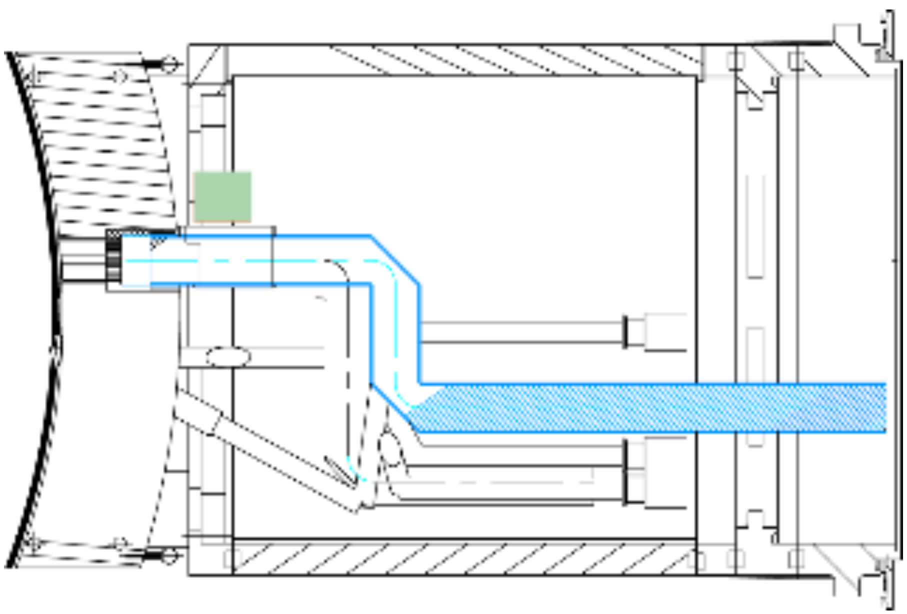
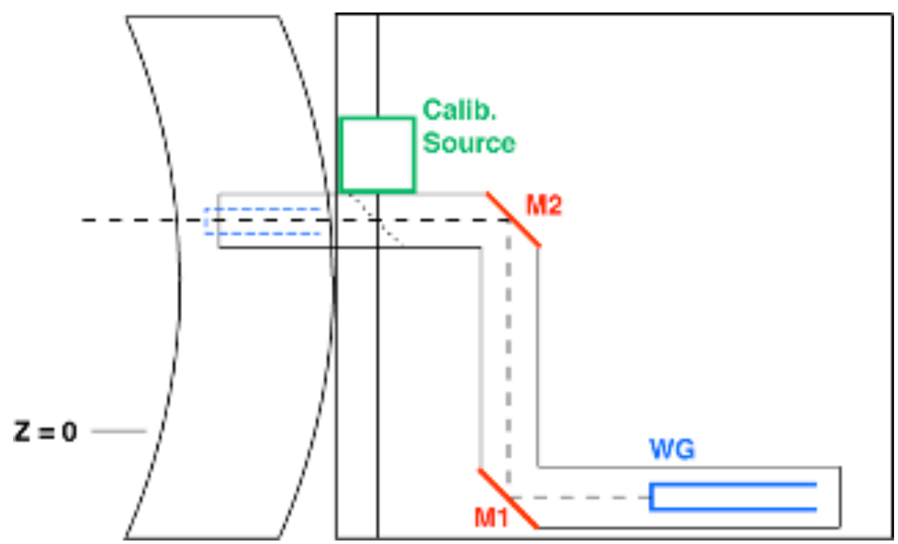




Specifications (cont.)

- Over the frequency range 100 GHz to 500 GHz an emissivity ≥ 0.95 is required.
- From 500 GHz to 1000 GHz, a relaxation of the emissivity requirement to ~0.75 would be acceptable.
- Above 1000 GHz, a further degradation of the emissivity is acceptable, but it is desirable that the source be usable up to ~1500 GHz.
- The temperature of the source should be able to be set anywhere up to ~650 °C, i.e. a radiation temperature at least 400 °K above the ambient temperature in the vacuum vessel (expected to be ≤200 °C).
- The active area of the source must be at least 200 mm in diameter, with a radiation temperature uniformity over this area of better than ±10 °K.
- The time required to reach equilibrium temperature should be as short as possible and not be longer than about 1 hour.
- The short term (~24 hours) stability of the source radiation temperature should be ~±2 °K. Over the long term (~3 years) the stability should be ~±10 K. This stability needs to be demonstrated under conditions that realistically simulate the ITER environment.
- Two sources will be installed in the vessel, and at least two more will be required for laboratory use. They should all have identical optical properties. The ex-vessel versions should operate in air.

Review ECE Calibration sources

- Most systems divert the optical system to an external calibration source
- Most operate at LN2 and room temperature for calibration
- Most operate at atmospheric pressure
- Exceptions
  - JET has hot source inside vacuum chamber but at atmospheric pressure
  - C-Mod LN2 source in vacuum but outside main vacuum vessel
- Source Material – high emissivity in microwave region of spectrum
  - Eccosorb – commercial open cell graphite loaded foam – room temperature and below
  - Macor – machinable fluorine rich glass ceramic – high temperature
  - Alumina - synthetically produced aluminum oxide
  - SiC – very high temperatures
- No in situ high temperature calibration source exists

Source Material SiC

- After reviewing the various blackbody materials, there is a clear choice for the ITER system, SiC
- SiC Properties
  - High thermal conductivity (~ 100W/mK) order of magnitude greater than other choices.
  - High emissivity in microwave region – long history of being used as microwave absorber.
  - Excellent high vacuum properties
  - SiC ceramic is made from SiC powder that is sintered in vacuum at 2100°C with high meting point (~2700°C).
  - Low thermal expansion coefficient ($4x10^{-6}$ °C) and no phase transitions

TABLE 4.16 Typical Parameters for Silicon Carbide

Parameter	Value
Density (g/cm^3)	3.10
Hardness (Knoop 100 g)	500
Modulus of elasticity (GPa)	407
Compressive strength (MPa)	4400
Fracture toughness ($MPa\text{-}m^{1/2}$)	7.0
Poisson's ratio	0.14
Thermal conductivity (W/m-K)	
25°C	290
150°C	160
Specific heat (W-s/g-K)	
25°C	0.64
150°C	0.92
TCE (10^{-6}/K)	3.70
Dielectric constant	40
Loss tangent	0.05
Volume resistivity (Ω-cm)	
25°C	$>10^{13}$
500°C	2×10^9

SiC (cont)

- The high neutron levels in ITER require that all materials have low activation rates.
- SiC has class C low-level activation waste. It has been considered as first wall material/blanket material. Reactor studies show that SiC could withstand the conditions of a first wall material under the neutron load and would therefore be suitable for the less demanding requirements of a calibration source.
- SiC system offers 3-4 orders of magnitude less activity than a low activation Ferritic Steel and the decay heat for the SiC drops sharply after shutdown, a salient feature for SiC.

Thermal Analysis

- SiC Properties used in thermal model

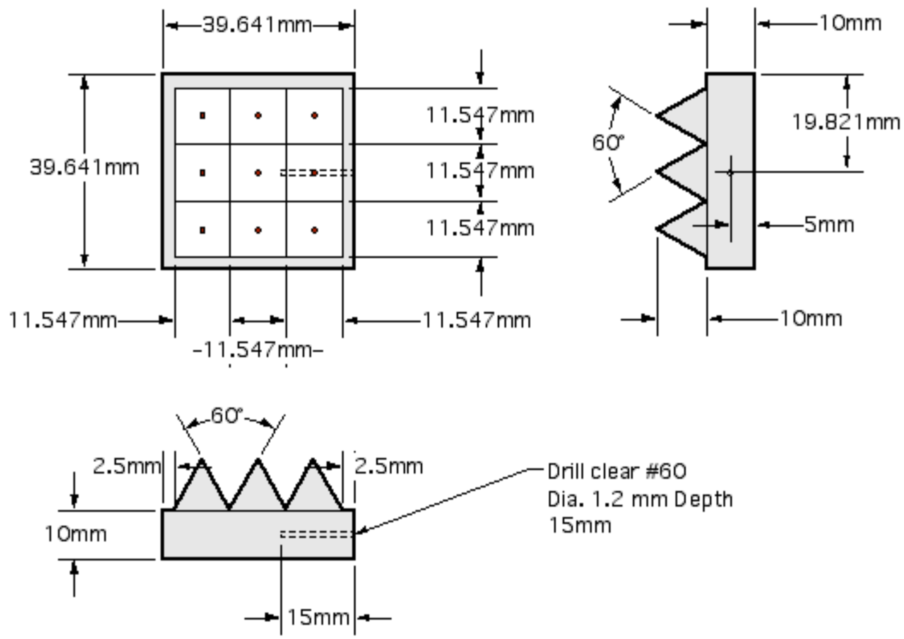
Source material	Density (kg/m^3)	Specific Heat (J/kg/K)	Thermal Conductivity (W/m/K)	Total Hemispherical Emissivity
Silicon Carbide	**3150**	**680**	**77.5**	**0.90**

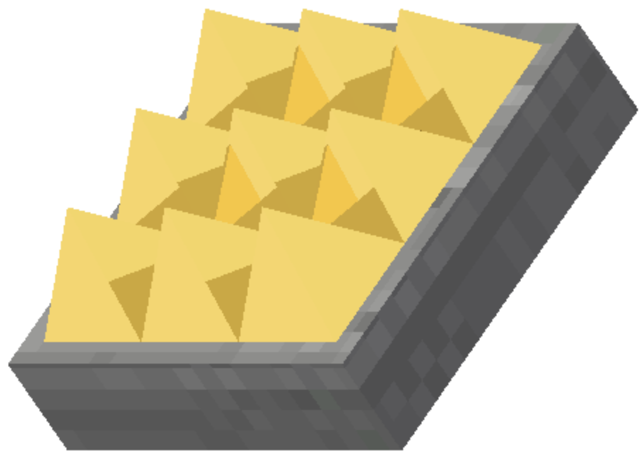
- Heat transfer calculations used in thermal model
  - Heat conduction
  - Natural convection
  - Radiation
- Code Used: Thermal analysis module of Patran[(1)]
  - 2d and 3d analyses
  - Variable mesh-size
  - Limitation of code: large number of faces with radiation exchange requires long computation times and large memory

(1): www.MSCsoftware.com

Thermal Model Small Source
Geometry

Model 3x3 surface (9 pyramids): Simplified case to test model – compare w/experiment

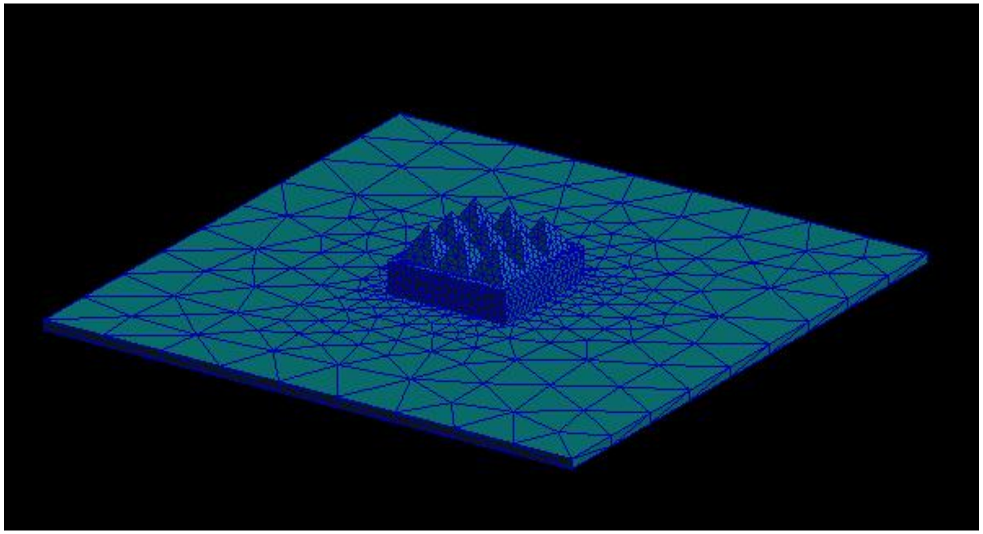




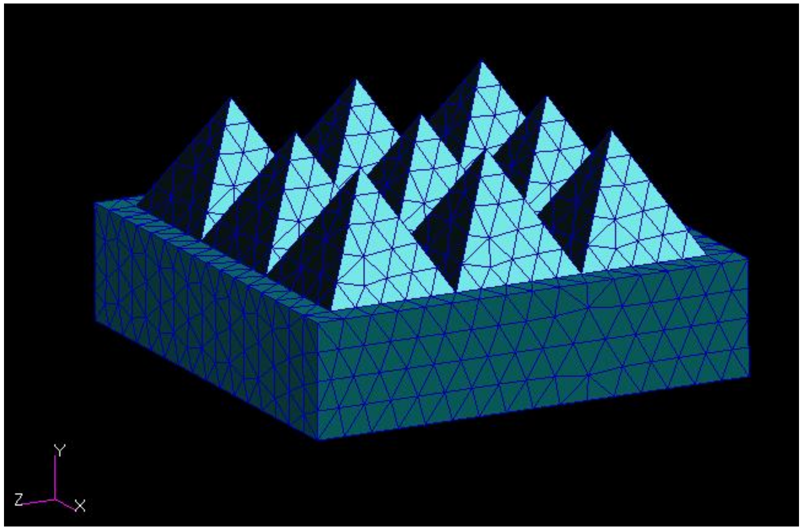
Thermal Model Small Source
FEA Mesh

- 3D FEA model built using SolidWorks(2) software
- Meshing and analysis performed using Patran /thermal module
- Total number of elements: 13,354

- Hot plate and small source mesh



- Small SiC source mesh



Hot Plate Material	Density (kg/m^3)	Specific Heat (J/kg/K)	Thermal Conductivity (W/m/K)	Total Hemispherical Emissivity
Ceramic	3940	837	32	0.90

(2): www.Solidworks.com

Thermal Model Small Source
Analysis Conditions

- Heating: Considered three temperatures
  - Hot plate temperatures: 350 ^{0}C, 500 ^{0}C, 800 ^{0}C
  - Perfect contact between hot plate and hot source assumed

- Cooling
  - Radiation cooling from hot source to ambient (20 ^{0}C)
  - Natural convection cooling from hot source to ambient (20 ^{0}C)

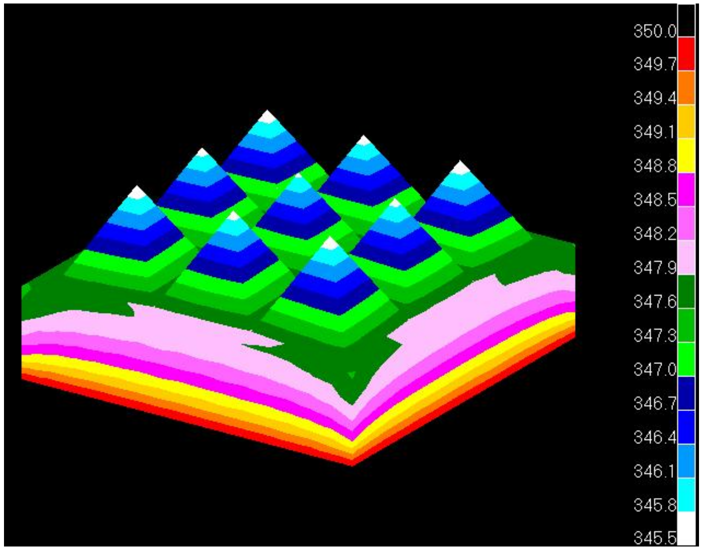
    (1) convection coefficient = 9.1 W/(m^{2}K) if hot plate temp. = 350 ^{0}C

    (2) convection coefficient = 10.3 W/(m^{2}K) if hot plate temp. = 500 ^{0}C

    (3) convection coefficient = 12.1 W/(m^{2}K) if hot plate temp. = 800 ^{0}C

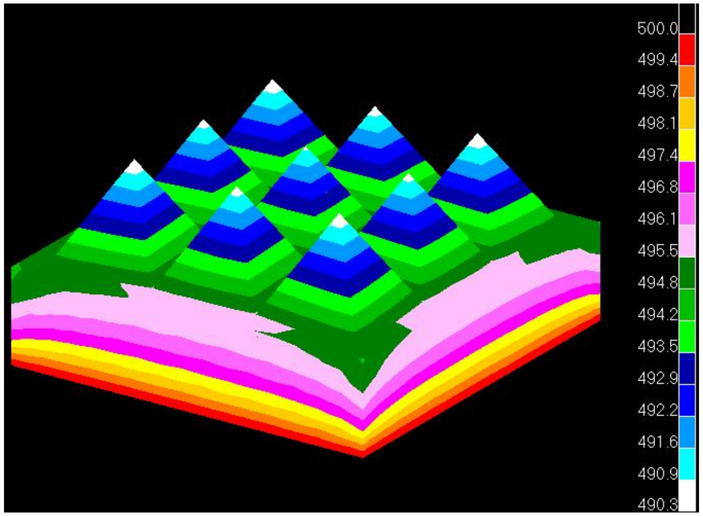
- Radiation view factor calculated for radiation energy exchange
  - between SiC side walls and hot plate
  - between SiC pyramid exterior faces and hot plate
  - between SiC pyramid interior opposite faces

Thermal Model Small Source
Results

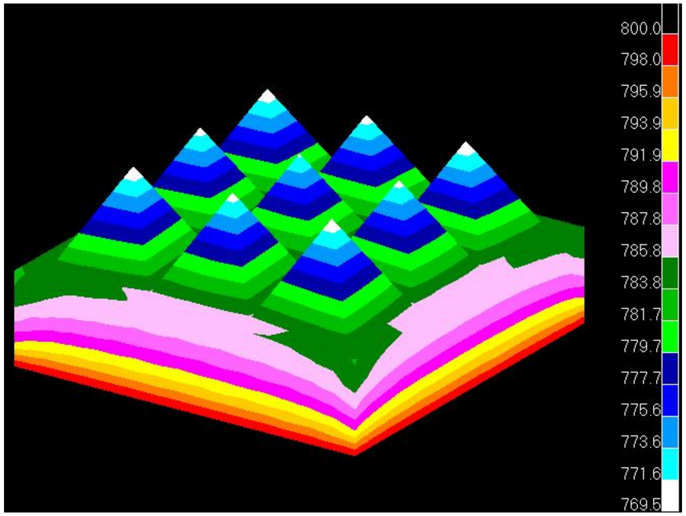


- Hot plate temperature = 350 ^{0}C: temperature difference between tip and base of pyramids $\Delta T = 1.8\ ^0$C

- Hot plate T= 500 ^{0}C: $\Delta T = 3.9\ ^0$C

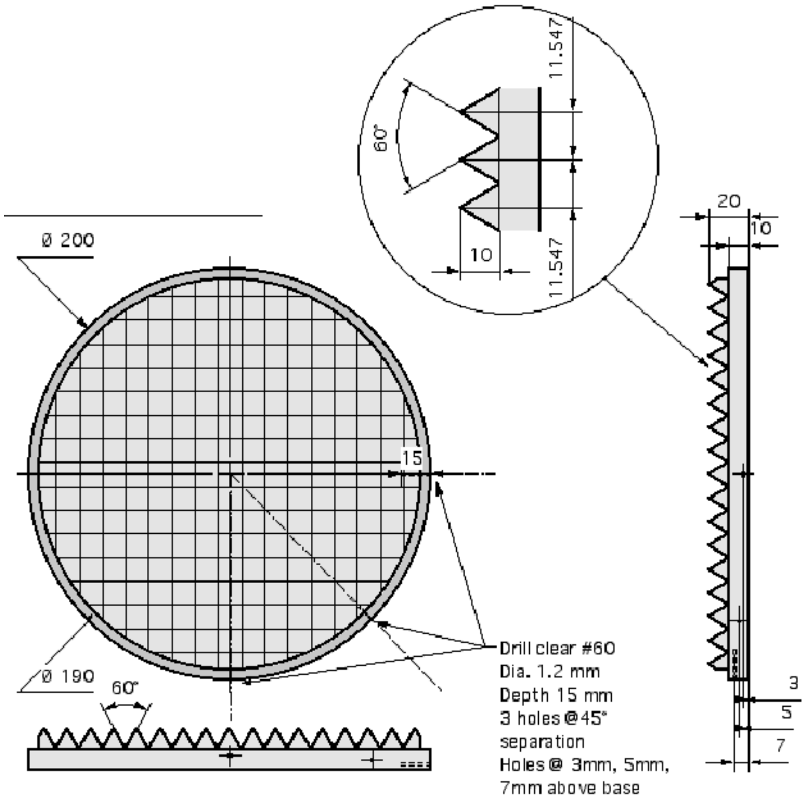


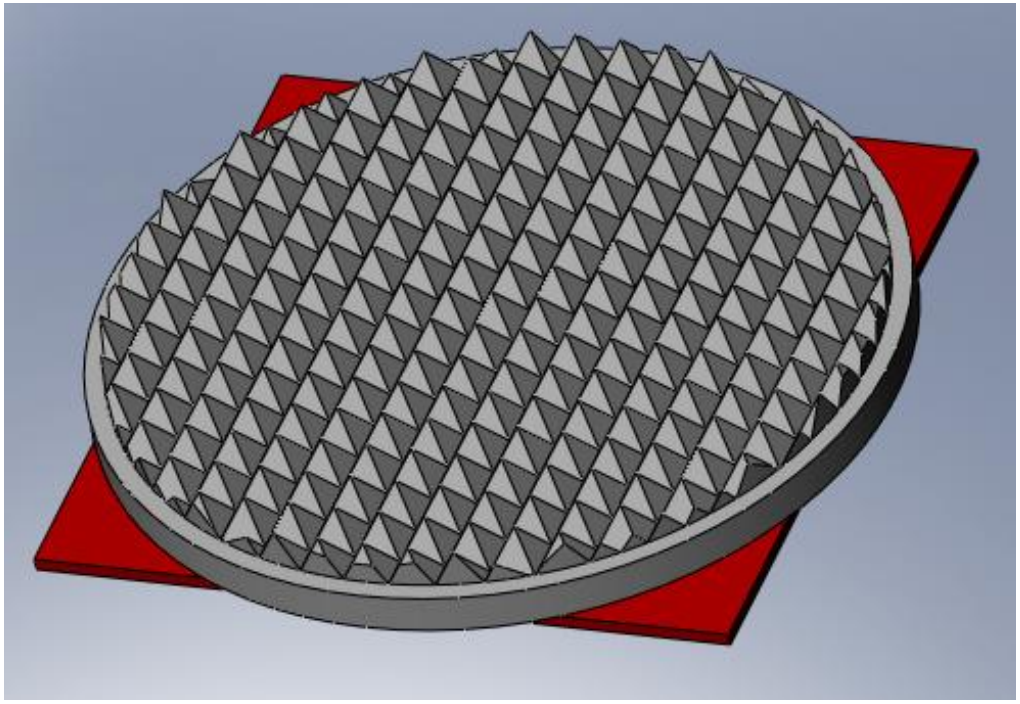
- Hot plate T= 800 ^{0}C: $\Delta T = 12.2\ ^0$C



Thermal Model Full Size Source Geometry

Full Size model – 200mm OD: ~ 200 Pyramids





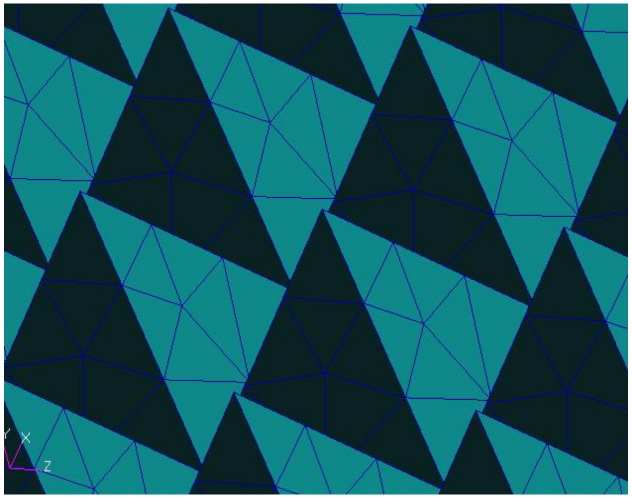
Model of large SiC hot source [200 mm OD] with hot plate [dimensions: 7" x 7" (178 mm x 178 mm)]

Thermal Model Full Size Source
FEA Meshes

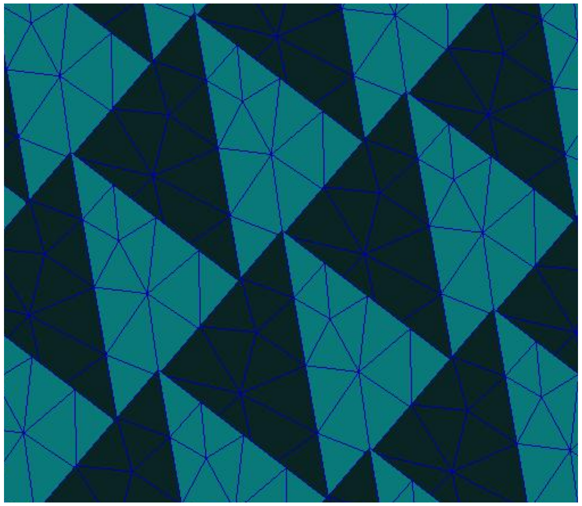
- 3D FEA model built using SolidWorks software
- Meshing and analysis performed using Patran /thermal module
- Considered 6 different mesh densities

Mesh #	1	2	3	4	5	6
# Elements	43414	56962	64762	93427	141530	290987

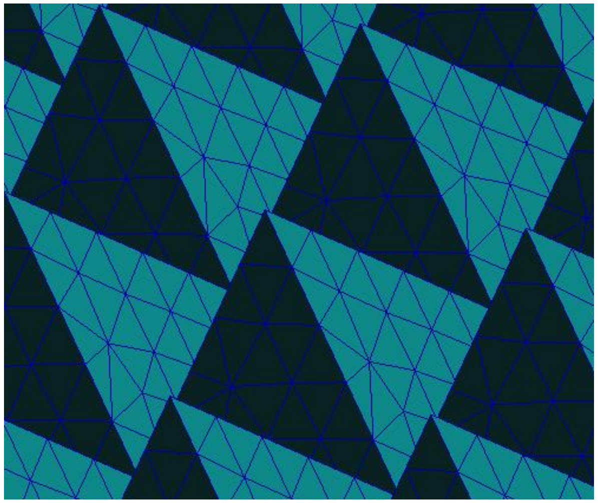
Mesh # 1



Mesh # 4



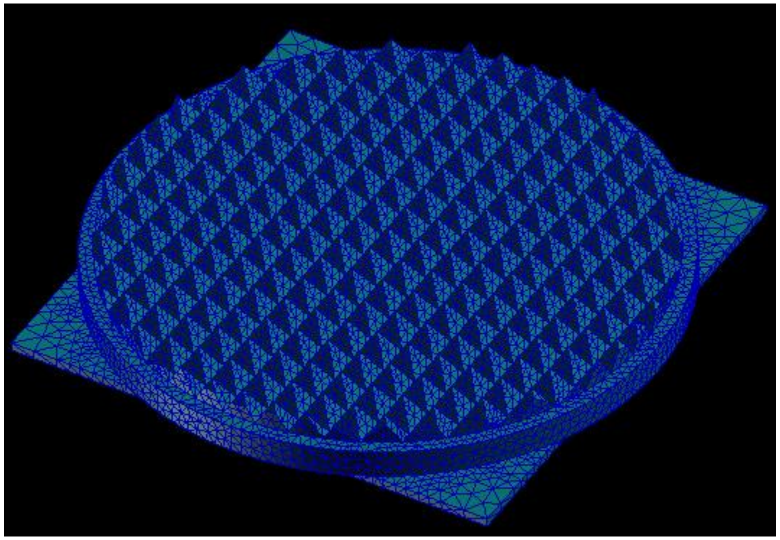
Mesh # 6

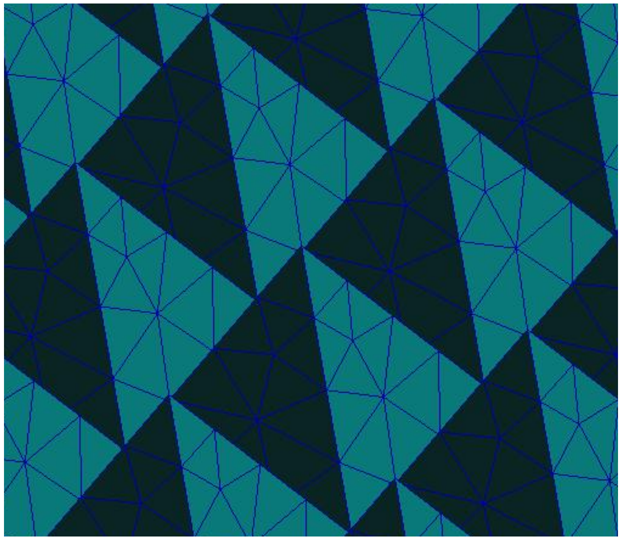


- Computational challenges
  - Varied mesh size and number of surface interactions to reduce computation time
  - Analysis of models with large number of elements were not successful on a PC

Thermal Model Full Size Source
Analysis Conditions

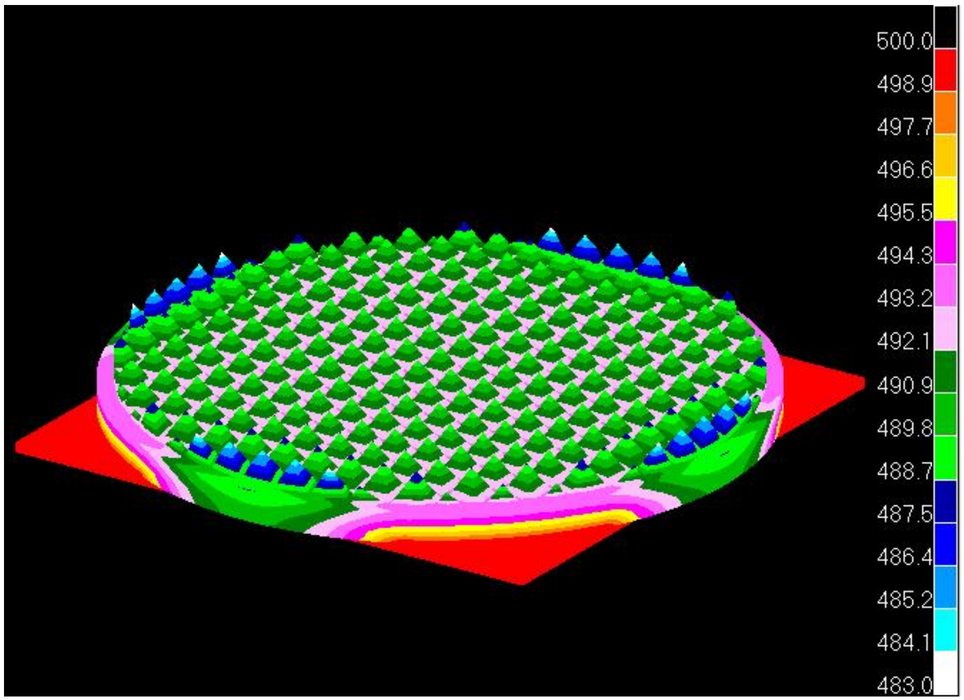
- Analyzed model with mesh # 4 (93457 elements)
- Heating
  - Hot plate temperature = 500 ^{0}C
  - Perfect contact between hot plate and hot source assumed
- Cooling
  - Radiation cooling from hot source to ambient (20 ^{0}C)
  - Natural convection cooling (h = 10 W/(m^{2}K)) from hot source to ambient (20 ^{0}C)
- No Radiation exchange

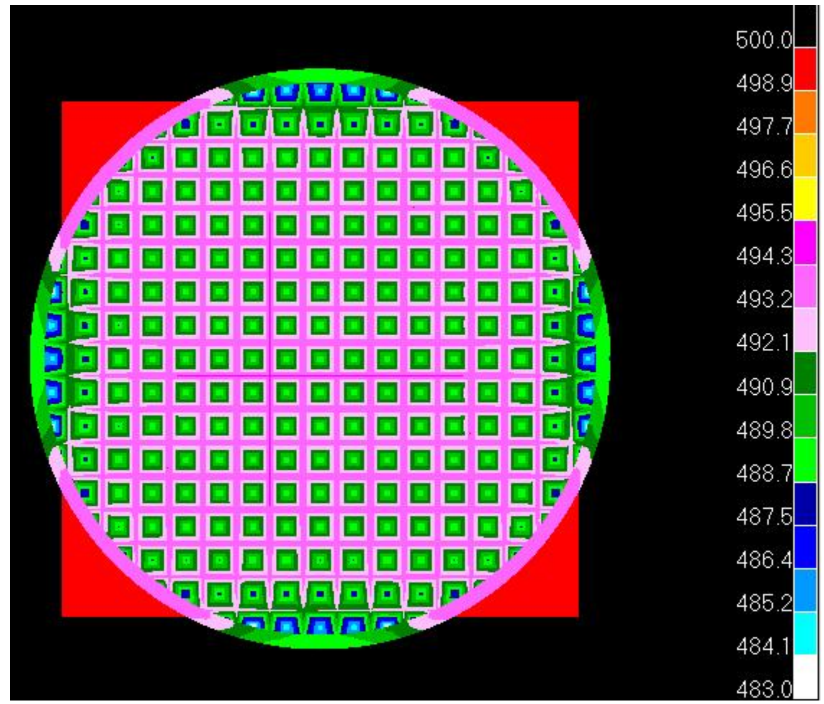




Thermal Model Full Size Source
Results

Steadystate temperature distribution (^{0}C)



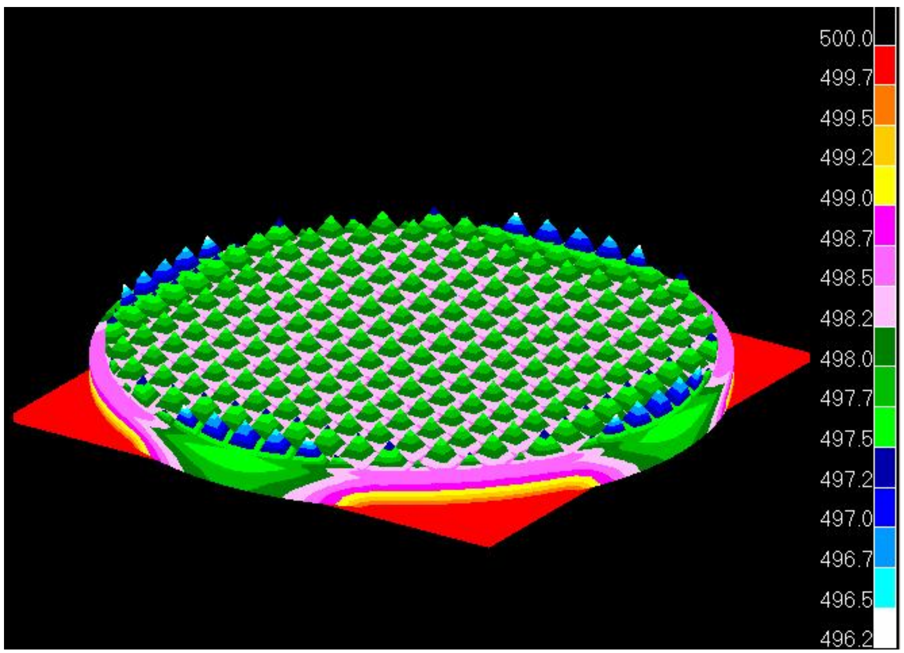


- **ΔT @ <u>center of source</u> < ~ 6 ^{0}C**
- **Extruding source edges cooler than center (as expected)**

Thermal Model Full Size Source Results (Cont'd)

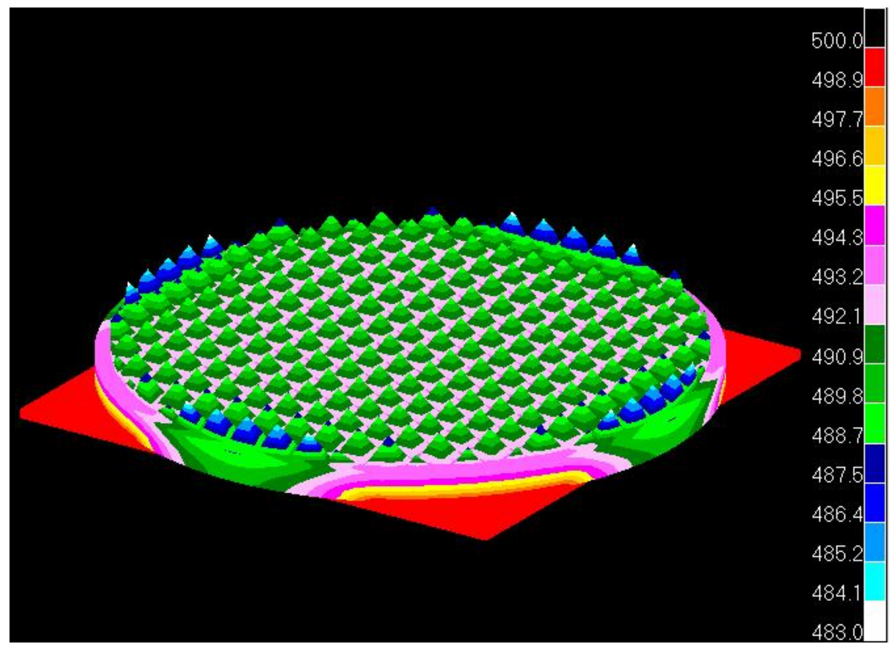
Effect of ambient radiation cooling

- Ambient Natural Convection ONLY



- **ΔT @ center of source < ~ 2 ^{0}C**

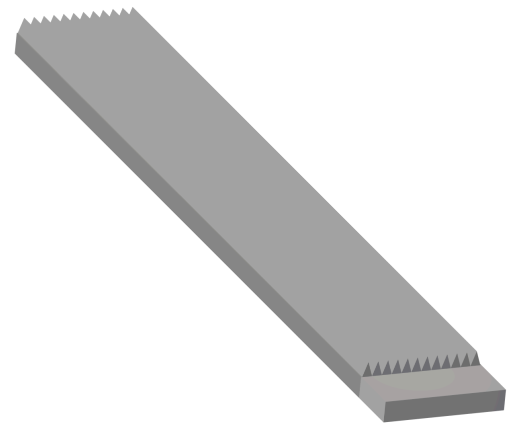
- Ambient Natural Convection AND Ambient Radiation Cooling



- **ΔT @ center of source < ~ 6^{0}C**

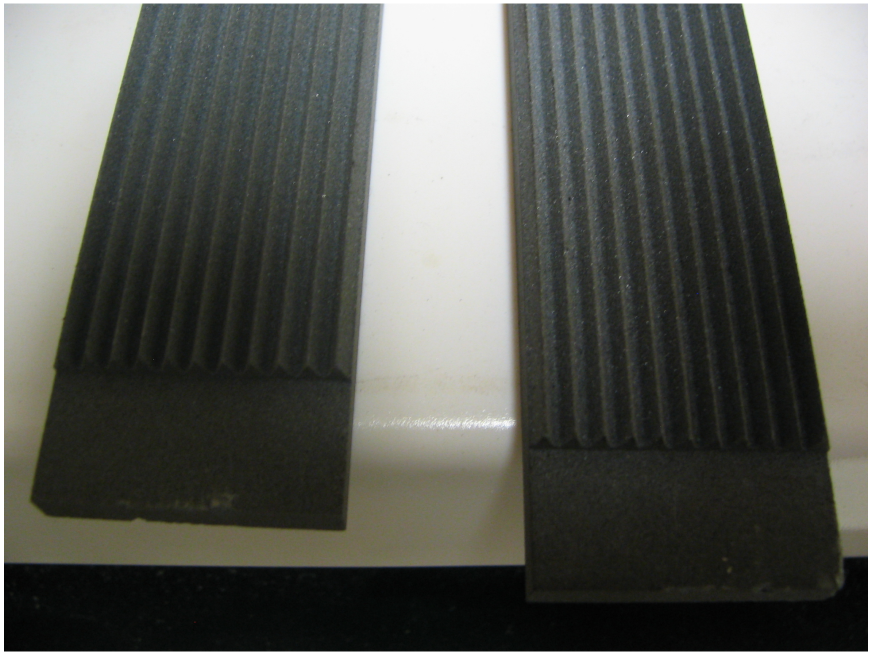
Experimental Models (Existing Piece)

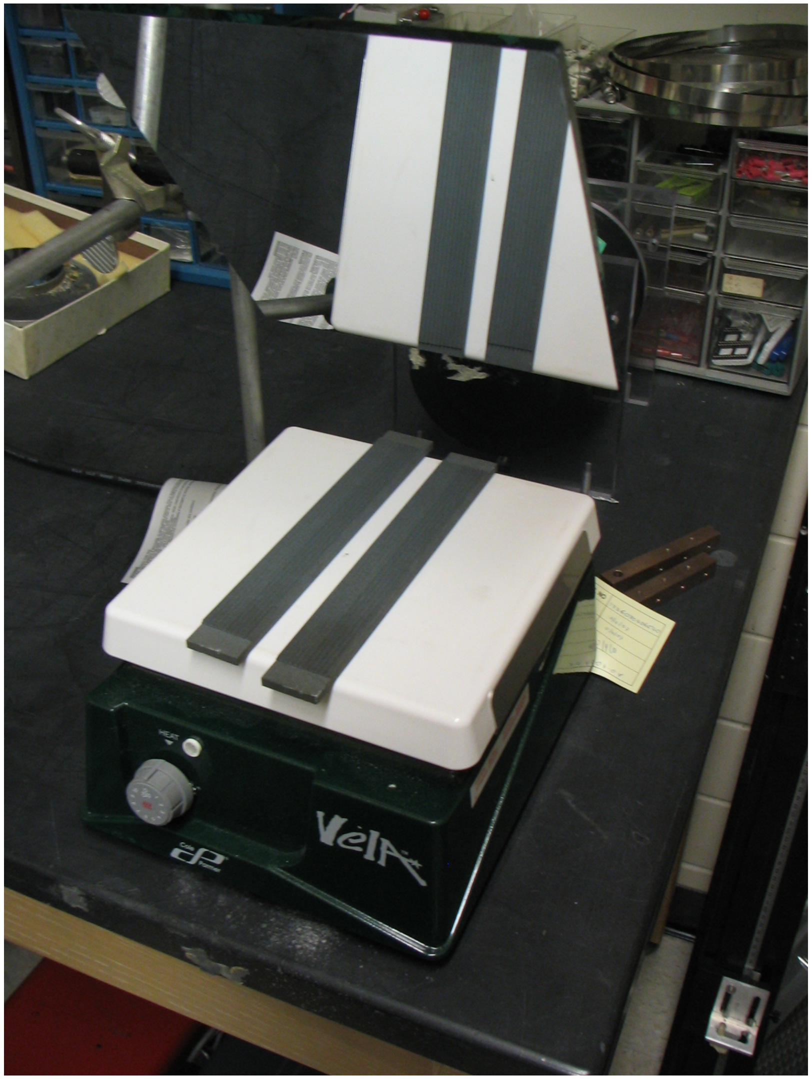
- Delay in delivery of test model
- Used existing SiC beam dump pieces
  - 35° grooves rather than pyramids
  - Base only 5mm in thickness
  - Grooves only 3 mm deep vs. 10 mm of planned parts



Preliminary Test with existing SiC absorbers

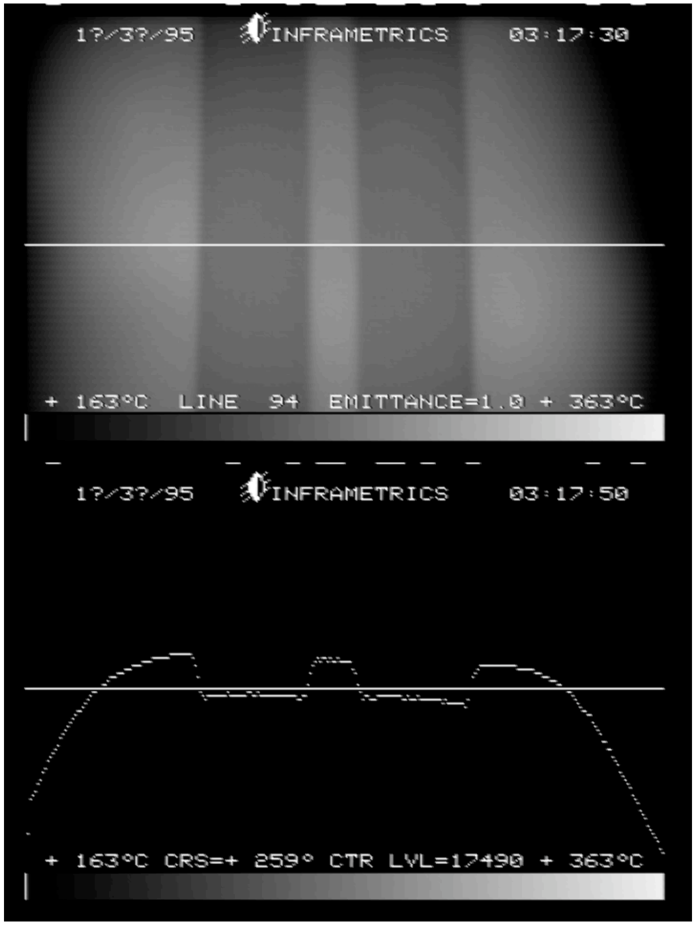
- SiC absorbers with 2mm grooves in only one direction.
- SiC two pieces, 1cm thick pieces 20cm x 5cm
- Heated to 250 °C on hot plate
- Viewed by IR Camera

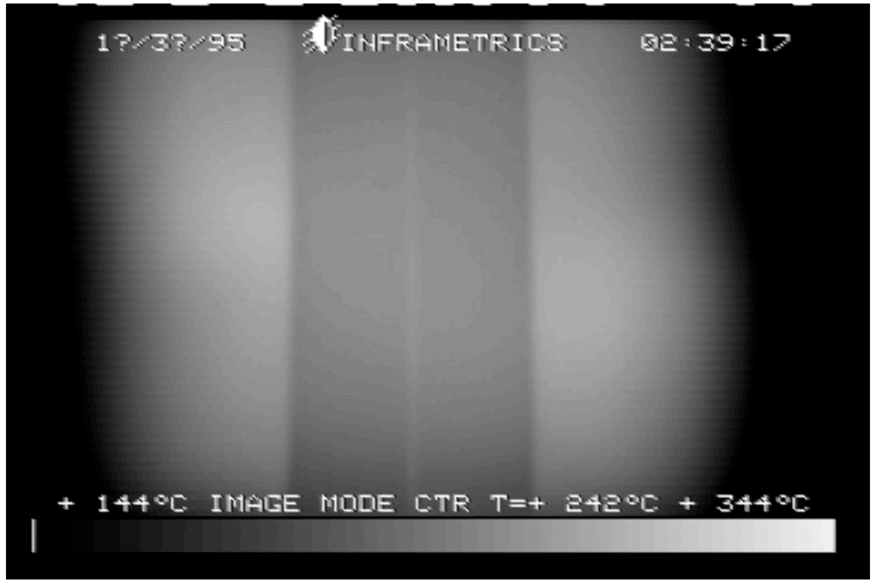


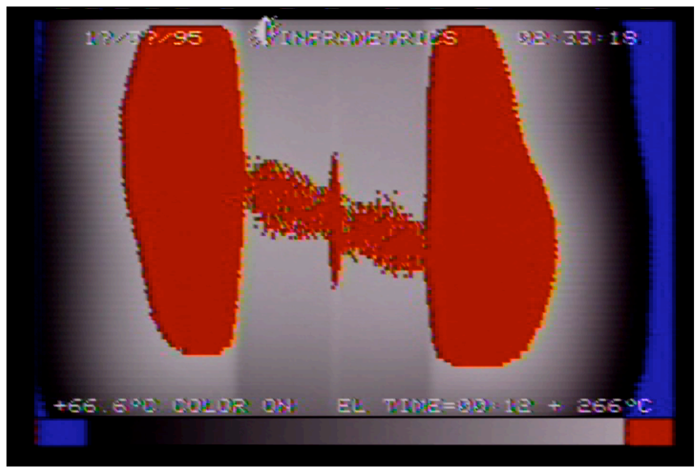


Thermal Image of Test Pieces

- Hot pate 240 °C (TC)
- SiC Surface temperature165 °C (TC)

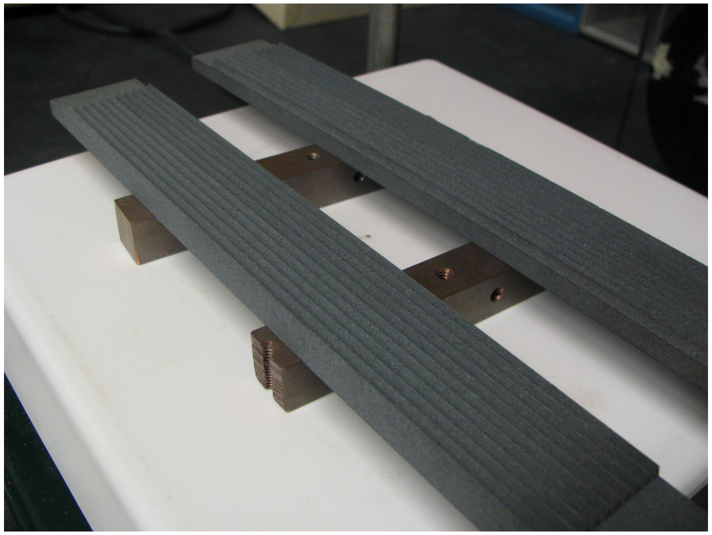


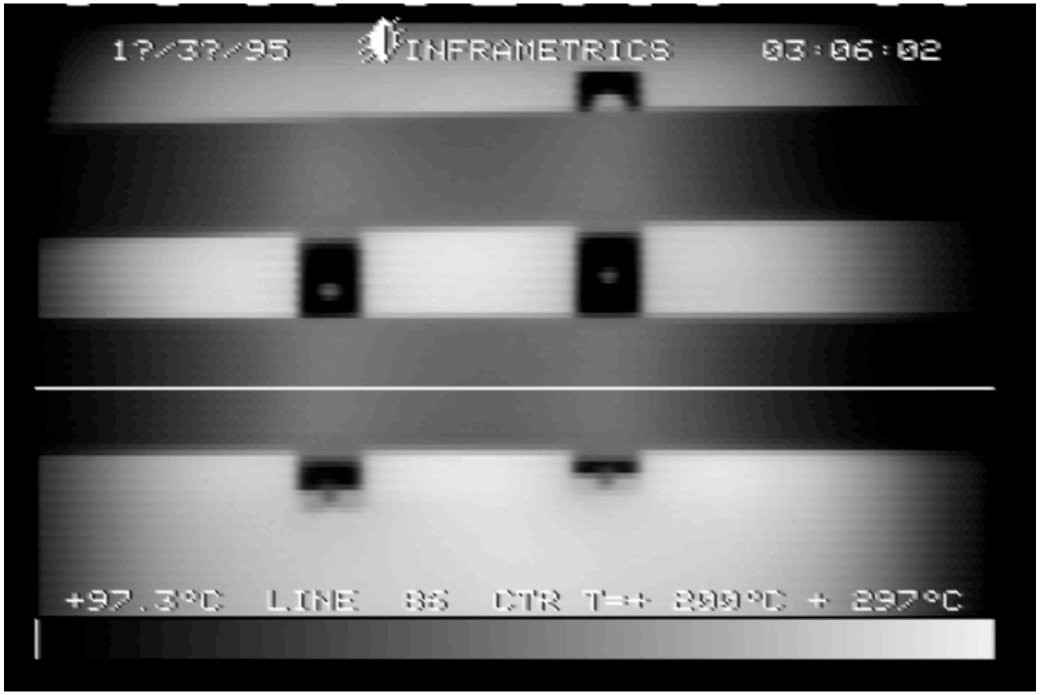


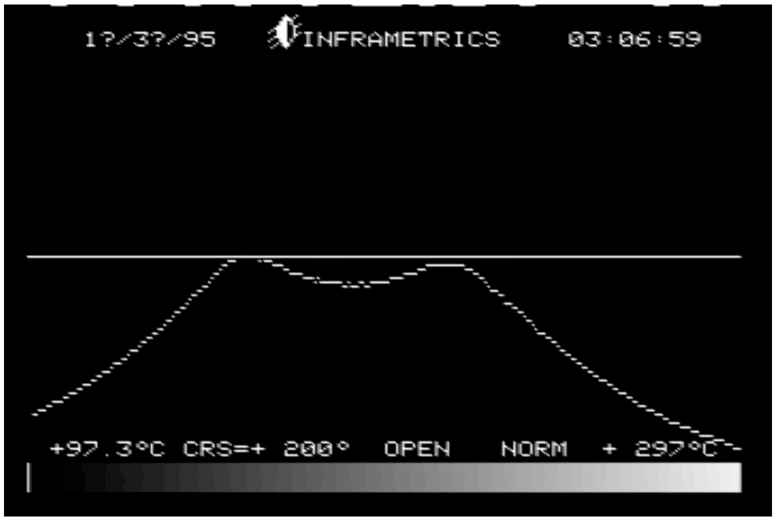


Non Uniform Heating

- Heat transfer through two ½" thick copper bars from hot plate
- Plate at 250 °C, Copper bars at 235°C, and SiC surface 170°C (all from TC)
- High thermal conductivity reduces the requirements on a uniform heating source.







Heating Methods

- A reliable in situ calibration source has not been demonstrated in any machine up to this time.
- The choice of heating method will be a significant engineering challenge to reliably heat the calibration source up to 1000 °C in an ITER environment. This work is just starting and no method has been determined.
- Methods
  - Electric resistance heating
    - Challenges
      - 1. High temperature terminal connections
      - 2. Bonding heater to SiC source
      - 3. Heating material susceptibility to contamination (neutrons and plasma)
      - 4. Aging effects on resistance may require increased supply voltage

Heating Methods (cont.)

- Induction Heating
  - Challenges
    - 1. Low electric conductivity of SiC requires an intermediate heater
    - 2. Bonding intermediate heater to SiC source
    - 3. Coil may be subject to high forces, need adequate structural support
    - 4. Intermediate heater and coil susceptibility to contamination (neutrons and plasma)

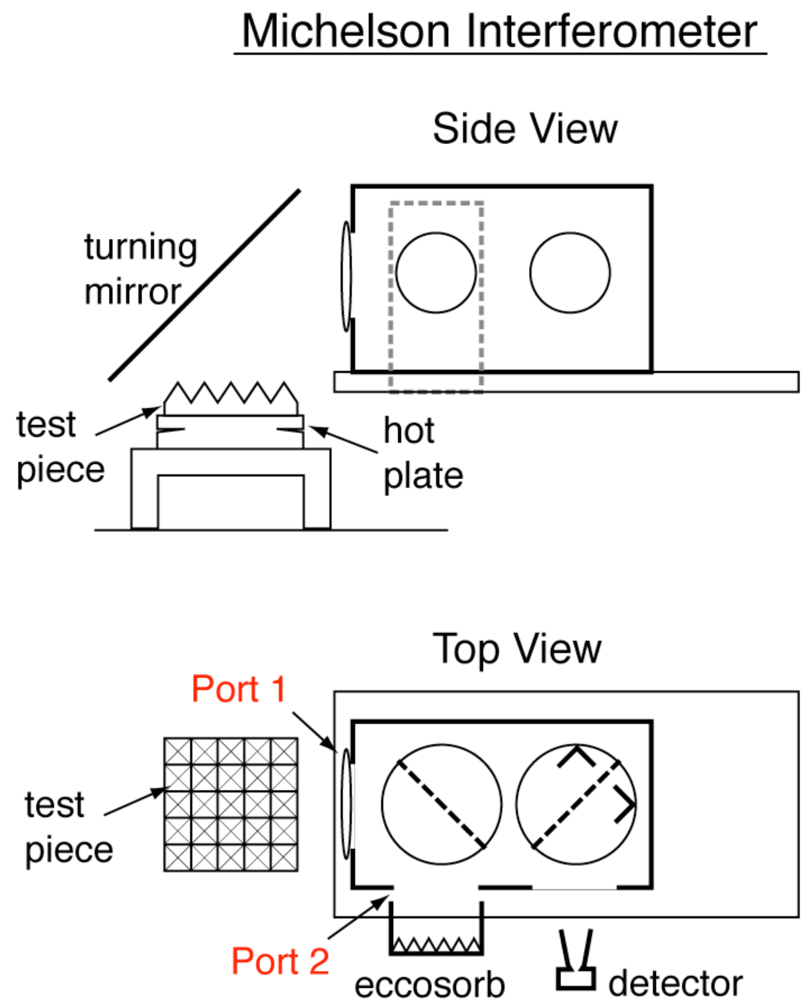
- Dielectric and Microwave heating
  - Challenges
    - 1. Need vacuum-compatible polar dielectric with high dissipation factor (loss tangent)
    - and adequate thermal and optical properties.
    - 2. Optimum heating frequency may interfere w/plasma frequencies (MHD…)
    - 3. Susceptibility to contamination (neutrons and plasma)
- Other non-conventional methods (?)

Emissivity Measurements

- Measurements made with Michelson interferometer
  - SPECAC model FSMI-4
  - useful freq. range: 60-1000 GHz
  - resolution ~6 GHz
  - typically avg. 10,000 scans
- Measurement technique
  - use LN and room temp. blackbody sources to determine instrument response function A_{RS}
  - measured intensity is temperature difference between Port 1 (test) and Port 2 (room temp.)

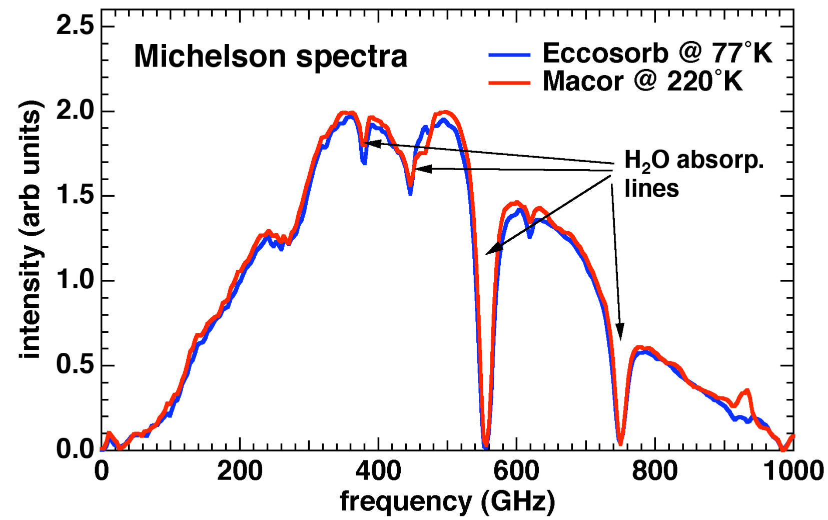
$$I_{meas} = |I_1 - I_2| = \frac{\omega^2 k}{8\pi^3 c^2}(T_1 - T_2) = \frac{I_{\det}}{A_{RS}}$$

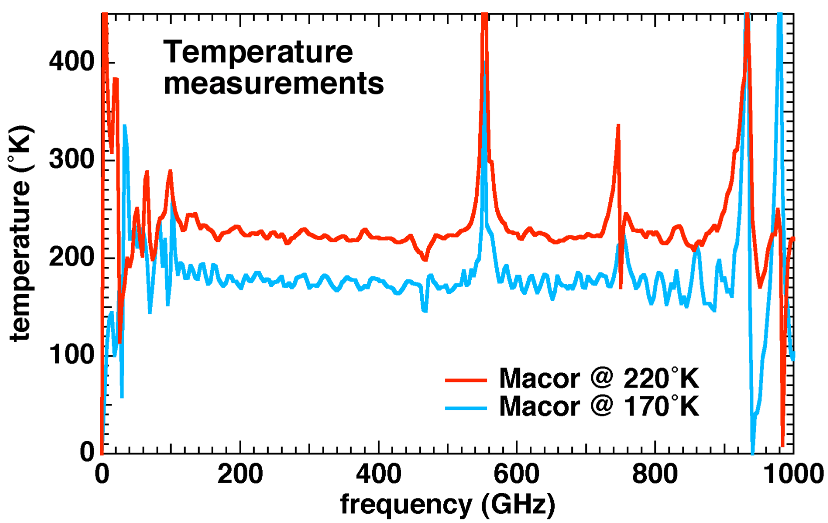
$$(T_1 - T_2) = \frac{8\pi^3 c^2}{\omega^2 k} \cdot \frac{I_{\det}}{A_{RS}}$$



Emissivity Measurement Data

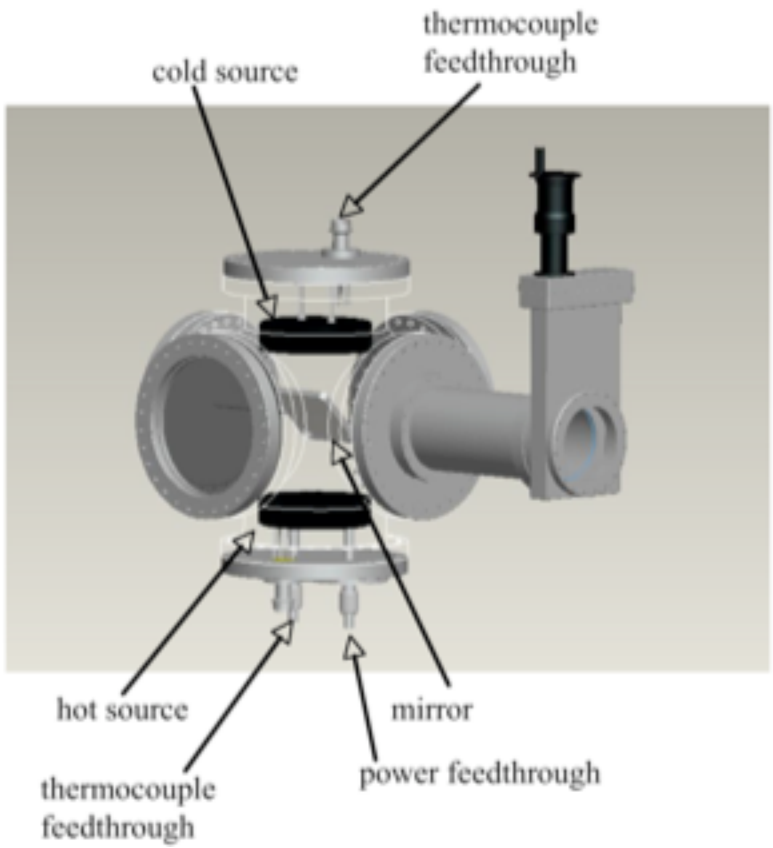
- Michelson measurements made of hot Macor dump
  - heated with hot plate
  - temperature of Macor measured with IR camera and TC probe
  - due to problems with the camera calibration, uncertainty of measurement is ±20˚C
- Raw spectrum of hot Macor very similar to LN source
- Temperatures are flat vs frequency outside of absorption lines.





Future Work

- A prototype heated source will be installed in vacuum test setup
  - Vacuum characteristics will be measured, out gassing rate and impurities.
  - Equilibration times and thermal stability will be monitored.
  - Thermal model will be compared with measurements to validate model. Radiation to to surrounding structure will be determined.
  - Heating uniformity with realistic prototype will be measured with IR camera
  - Full emissivity measurements from 100 GHz to over 1000 GHz will be determined using Michelson interferometer.
  - Data from this work will be used to design calibration source for ITER.



Poster available online at http://www.frc.utexas.edu/meetings/HTPD08/